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The Transfer of Heat and Hydrophobic Substances During Burning[1]

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ABSTRACT

Wet and dry sand was tested for water repellency, after burning pine litter (*Pinus coulteri* D. Don). Four conditions were studied: a burn of 25 min over dry or wet sand and a burn at 5 min over dry or wet sand. The thickest and most intense water-repellent layer was produced by a 5-min burn over dry sand. Although organic materials were translocated deeper in the dry sand during the 25-min burn (down to 4 cm), some of the water repellency was destroyed in the upper 1-cm layer. In wet sand, water repellency was concentrated in the upper 0- to 1.5-cm layer. The translocation of hydrophobic substances and resulting water repellency depends on changes in their polarity and oxidation state. Relationships developed for fire over a dry soil may not adequately account for movement of organic substances in a moist soil. These results suggest prescribed burning should be done when the soil is moist on areas where water repellency is a problem.

Additional Index Words: **water repellency, soil water, organic matter.**

WATER REPELLENT SOILS produced by wildfires on chaparral watersheds are commonly found in southern California (4). A water-repellent layer is formed when organic substances move from burning litter into the underlying soil during a fire (6). Water repellency becomes intensified when heat pulses move downward through the soil and "fixes" some of the more polar hydrophobic substances. Less polar substances are revolatilized, broadening the water-repellent layer (5). The temperature required for "fixing" and revolatilization appears to exceed 250°C (5, 8).

Soil physical properties can influence the translocation of organic substances. Soil texture can modify the thickness and intensity of the water-repellent layer (3). Coarser textured soils can acquire a much thicker and more intense water-repellent layer than finer textured soils. This difference may be due in part to the amount of particle surface area covered with organic substances. A given amount of organic material probably coats less particle surface in a finer textured soil than in a coarser textured soil.

Soil water also affects the translocation of organic substances by altering temperature gradients in soil during a fire. The nature of the particle surface could also be modified by soil water. The effect of soil water on water repellency has practical implications because fire is used widely as a land management tool. For example, controlled burning has been used for range improvement, fire hazard reduction, and slash disposal. Understanding how soil water influences water repellency would be important when preparing guidelines for controlled burning so burning could be done when water repellency was minimized.

This paper reports some results of studies on the translocation of hydrophobic substances in wet and dry sand during a series of laboratory burning experiments, and offers additional evidence on the possible mechanisms responsible for fire-induced water repellency.

EXPERIMENTAL PROCEDURE

The burning apparatus we used consisted of a heat source and soil container (1, 3). The heat source was a series of muffle furnace heating coils embedded in an asbestos box that was placed over a soil container during burning. The soil container was made of asbestos sheets and was filled with either dry or wet sand to within 2 cm of the top of the container. The upper 2 cm of the container was filled with partially decomposed Coulter pine (*Pinus coulteri* D. Don) litter that had been ground previously in a Wiley mill to pass a 2-mm sieve. The sand was pure quartz of medium particle size (0.50-0.25 mm) having a surface area of 77 cm^2/g. The wet sand contained about 6.3% water on a weight basis. After

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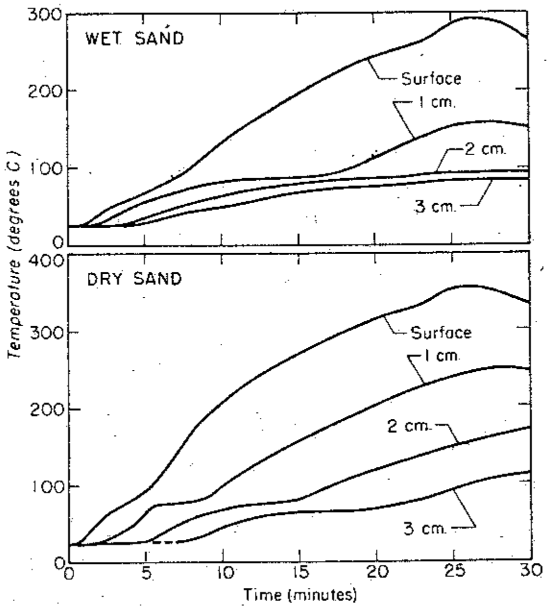

Fig. 1—Temperature at four depths when pine litter was burned over wet and dry sand for 25 min.

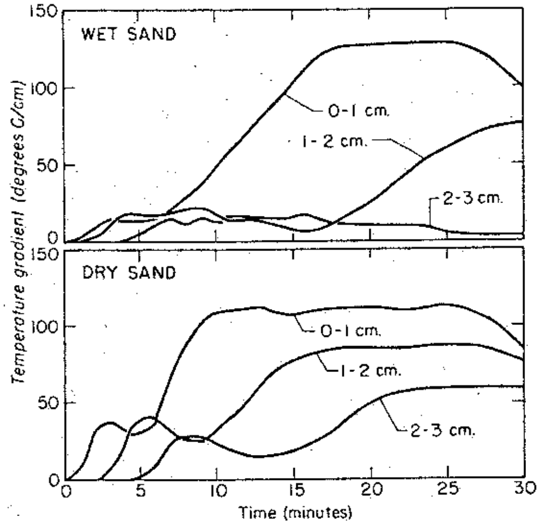

Fig. 2—Temperature gradients developing when pine litter was burned over wet and dry sand for 25 min.

preheating to about 760°C, the coil was placed on the soil container for 5 min during one series of burning experiments and for 25 min for another set. Each burning time was replicated three times for both dry and wet sand.

Chromel-alumel thermocouples were placed at 1-cm intervals of depth to 10 cm, and at 2-cm intervals for the remaining depth. Temperatures were recorded continuously with a multichannel potentiometric recorder at each depth during burns, and for 2 hours after each burn. After cooling, the sand was removed by 0.5-cm layers in the upper 2 cm, by 1-cm layers from 2-8 cm, and by 2-cm layers in the 8-14 cm depth. Each layer removed was air dried until it contained about 0.5% water and then tested for water repellency by placing a water droplet on the surface and measuring the time required for the droplet to be absorbed.

Total organic matter content of the layers removed from the upper 2 cm was determined by first drying the sand for 2 hours at 105°C, weighing the sample, then igniting the dried sample at 700°C for 4 hours, and reweighing (7). Organic carbon in each layer down to at least 4 cm was determined by oxidation with potassium dichromate (10). Sand samples of each layer were extracted by shaking in a solution of benzene and methanol (1:1, vol/vol) for 1 hour. The solution was then decanted and fresh solvent mixture added after which shaking was continued for another 30 min. The ratio of the extractant to sand was about 2:1 (vol/wt). The solvent was again decanted, and the sand washed with fresh solvent before being dried in a hood. The organic matter remaining on the extracted sand was then determined by dry combustion (700°C for 4 hours). Organic matter removed by this repeated extraction was expressed as a percentage of the total organic matter determined by dry combustion for layers in the upper 2 cm of sand. Below the 2-cm level, tiny amounts of organic matter and organic carbon made this analysis unreliable.

RESULTS AND DISCUSSION

Temperature and Temperature Gradients

Temperatures at the surface and in the underlying layers during the 25-min burn were much lower in wet sand than in dry sand (Fig. 1). Maximum surface temperature in the dry sand was 350°C as contrasted to 285°C in the wet sand. Temperatures in the underlying wet sand probably did not exceed 100°C until most of the water had vaporized and moved out of each layer. Temperatures exceeded 100°C down to 4 cm in the dry sand during the 25-min burn, but to only 2 cm in the wet sand. Lower soil temperatures have been reported under field conditions when the soil is moist (9).

Temperature gradients developed faster in the dry sand than in the wet sand during the 25-min burns (Fig. 2). For example, temperature gradients of over 100°C/cm developed across the 0- to 1-cm layer of the dry sand within 9 min as contrasted to wet sand where it took almost 15 min (Fig. 2). Temperature gradients also developed more rapidly in the 1- to 2- and 2- to 3-cm layers of the dry sand than in the wet sand. Temperature gradients are believed partially responsible for translocating hydrophobic substances downward in soil during fire (1).

Although not shown here, the temperature gradients developed during 5-min burns were similar to 25-min burns, but the maximum temperatures and temperature gradients were less. Temperatures at the surface of the dry sand columns did not exceed 250°C and the maximum temperature difference across the 0- to 1-cm layer was only 75°C. In the wet soil the maximum surface temperature reached only 150°C during 5-min burns.

The appearance of the temperature gradients over time in the dry sand during 5- and 25-min burns suggests vaporization and condensation of material was occurring. In almost every case the temperature gradients increased rapidly in magnitude at the start of burning, decreased for a short time, and then increased until the experiment ended (Fig. 2). This behavior was sequential with depth—first occurring in the 0- to 1-cm layer, followed by the 1- to 2-cm layer, and finally in the 2- to 3-cm layer. Temperature gradients across the 0- to 1-cm layer increased during the first 5-10 min of burning (Fig. 2), because the surface temperature rose more rapidly than at the 1-cm depth (Fig. 1). From 10-25 min, surface temperatures and those at 1 cm increased at similar rates causing the temperature gradients to stabilize at about 110°C/cm. Gradients across the 0- to 1- and 1- to 2-cm depths showed similar patterns, but at later times (Fig. 2).

The temperature gradients probably assumed this shape

Table 1—Water drop penetration time, organic matter, and organic carbon in dry and wet sand under pine litter burned for 5 and 25 min.

Burning condition	Depth	Water drop penetration time	Organic matter	Organic carbon	Organic matter as organic carbon
	cm	sec	%		
5 min over dry sand	0 -0.5	207	0.178	0.108	61
	0.5-1	>3600	0.065	0.045	69
	1 -1.5	>3600	0.032	0.029	91
	1.5-2	>3600	0.016	0.021	
	2 -3	48		0.015	
	3 -4	0		0.011	
25 min over dry sand	0 -0.5	0	0.084	0.052	62
	0.5-1	>3600	0.042	0.029	69
	1 -1.5	1400	0.028	0.023	82
	1.5-2	360	0.021	0.019	90
	2 -3	328		0.014	
	3 -4	57		0.010	
5 min over wet sand	0 -0.5	>3600	0.231	0.163	71
	0.5-1	600	0.083	0.056	67
	1 -1.5	60	0.042	0.032	76
	1.5-2	<10	0.019	0.016	84
	2 -3	0		0.014	
	3 -4	0		0.010	
25 min over wet sand	0 -0.5	>3600	0.216	0.144	67
	0.5-1	>3600	0.051	0.039	76
	1 -1.5	420	0.028	0.022	79
	1.5-2	10	0.014	0.015	93
	2 -3	0		0.009	
	3 -4	0		0.006	

in dry sand because heat necessary for vaporization was absorbed by the litter layer rather than being immediately transferred downward in the sand by conduction and convection. After the organic substances had been vaporized, they moved downward along temperature gradients to a lower depth where they condensed and increased the temperature of that layer. Later temperatures in the condensation layer increased and substances were again vaporized and moved deeper, causing a depression in the temperature gradients across the next lower depth. Although this analysis is based on temperatures measured at 1-cm intervals, the process was probably continuous and occurred sequentially as substances were translocated downward. Part of the material moving downward was hydrophobic because some of the sand layers became extremely water repellent. In wet sand the temperature gradients did not show a pronounced depression, but instead remained low for awhile before increasing. Magnitude of temperature gradients in the wet sand probably increased after water was translocated out of a given layer.

Distribution of Water Repellency

Water content and burning time both influenced the distribution and intensity of water repellency (Table 1). Water-repellent substances were translocated deepest during the 25-min burn over dry sand and were detectable in the 3- to 4-cm layer. However, a 25-min burn destroyed water repellency in the upper 0.5-cm layer of dry sand, where the maximum temperature reached about 350°C. Previous experiments have shown that temperatures of 270 to 300°C can destroy organic substances responsible for water repellency (2, 5, 8). Steep temperature gradients during the early part of the 25-min burn may have caused translocation of organic substances into deeper depths of the dry sand.

The most severe water-repellent conditions were produced by a 5-min burn over dry sand. Although water repellency was not as deep under 5-min burn as the 25-min burn, it was more intense—particularly in the layers between 0.5 and 2 cm. In the wet sand, water repellency was concentrated nearer the surface and was very intense in the upper 0-1.5 cm of sand during the 25-min burn. The 5-min burn over wet sand concentrated water repellency primarily in the upper 0.5-cm layer, although it was detectable down to 2 cm. The surface temperature of the wet sand was not high enough during the 5- and 25-min burns to destroy water repellency (the maximum temperature was only 280°C during the 25-min burn), although fairly steep temperature gradients developed across the 0- to 1-cm layer (130°C/cm after 20 min). These steep gradients were probably responsible for producing the extreme degree of water repellency in the upper 0.5- to 1.5-cm layer of the wet sand during the 25-min burn (Table 1).

Organic Matter and Organic Carbon

Measurable amounts of organic matter and organic C moved downward into the upper 2 cm of sand during the burning experiments (Table 1). Below 2 cm, only small amounts of organic C were detected. Neither the amount of organic C nor organic matter were closely related to water repellency. However, the percentage of organic C in the organic matter seemed related to the degree of water repellency (Table 1). For example, in the 0- to 0.5-cm layer, of both the 5- and 25-min burns over dry sand, 60% of the organic matter was C and neither sample showed extreme water repellency. In both the burns of 5 and 25 min over wet sand, about 70% of the organic matter in the 0- to 0.5-cm layer was C and both samples showed extreme water repellency. In all other samples (except the 5-min burn over wet sand), the 0.5- to 1-cm layer showed extreme water repellency and the C content of the organic material was close to, or over 70%.

The extractability of organic material, which increased with depth (Table 2), was not necessarily related to the degree of water repellency. In dry sand, water repellency was greatest at depths where the extractable organic matter exceeded 45%. In contrast, with wet sand water repellency was greatest where extractability of organic matter was least (i.e., in the surface layers).

The results of the burning experiment over dry sand are consistent with the hypothesis describing the translocation of hydrophobic substances proposed by Savage (5). According to that hypothesis organic matter (both hydrophobic and hydrophilic) in plant litter move downward in soil during fire. The more polar substances condense and are fixed in the upper layers by heat pulses of 250°C or greater. Material not fixed in place is moved downward in the profile by the heat pulse and a natural fractionation of the more nonpolar organic substances occurs. Chemical analysis by Savage (5) indicated organic substances exposed to high temperatures (over 250°C) have higher oxygen contents, are more polar, and possess less hydrophobicity than those substances that are not heated to these temperatures.

The organic matter found after burning in the surface layer of the dry sand (0-0.5 cm) contained less organic C than a comparable layer in wet sand. Also, organic sub-

Table 2—Temperature and percent of extractable organic matter in the upper layers of wet and dry sand under pine litter burned for 5 and 25 min.

Burning condition	Depth	Maximum temperatures†	Percent of organic matter extractable	Water drop penetration time
	cm	°C		sec
5 min over dry sand	0 -0.5	254-233	28	201
	0.5-1	233-212	47	>3600
	1 -1.5	212-192	85	>3600
	1.5-2	192-172	100	>3600
25 min over dry sand	0 -0.5	353-320	27	0
	0.5-1	320-287	52	>3600
	1 -1.5	287-252	79	1400
	1.5-2	252-216	100	360
5 min over wet sand	0 -0.5	175-147	42	>3600
	0.5-1	147-118	73	600
	1 -1.5	118- 98	100	60
	1.5-2	98- 79	100	<10
25 min over wet sand	0 -0.5	287-232	31	>3600
	0.5-1	232-177	63	>3600
	1 -1.5	177-140	100	420
	1.5-2	140-103	100	<10

† Range of maximum temperatures over three replicates.

stances in the surface layer of the dry sand were strongly adsorbed and difficult to extract. The temperature of the surface layer in the dry sand under both the 5- and 25-min burning times exceeded 250°C. The greater polarity of substances in the surface layer probably made them less easy to extract. Also, the percentage of organic C in the organic matter was lower, indicating a higher oxidation state which again agreed with the condition of greater polarity and lower degree of water repellency. Natural fractionation described by Savage (5) apparently continued downward in the deeper layers of the dry sand with substances that condensed at the lower levels being most easily extracted.

The fractionation of organic compounds was not well defined during the 5- and 25-min burns over wet sand. Organic material in the upper layers was still as difficult to extract as in dry sand. However in the surface layer (0-0.5 cm), water repellency was much greater in wet than in dry sand. More total organic matter remained in the upper layers of the wet sand than in the dry sand. This difference was expected because the temperatures during the burn were lower in the wet sand. Water probably interfered with the normal fractionation of organic substances along the temperature gradients that commonly occur in dry sand (Table 2). Apparently both highly water-repellent substances and polar compounds remain in the surface layers of the wet sand where they produce a high degree of water repellency.

Practical Implications

Although the burning experiments on dry and wet sand were done in the laboratory, they suggest some useful relationships for predicting changes in water repellency that can occur during a wildfire or prescribed burn. For example, a 5-min burn over dry sand might best approximate heat transfer occurring during wildfires or prescribed burns in standing brush. The 25-min burn probably simulates the heat pulse under a pile of burning brush or in small localized "hot spots" during wildfire. Dry sand most nearly represents the soil water condition present during late summer and early fall wildfires in southern California. Results from the burns over wet sand may indicate useful relationships existing during a burn in spring or fall when the soil is moist.

The data suggest that light burning on a dry soil produces a thick and highly water repellent soil layer. This condition may explain why wildfires in late summer and early fall produce extremely water repellent soil in southern California. These results should discourage the burning of standing brush over dry soil. Burning 25 min over a wet sand produced the next worst condition. Consequently, broadcast burning of brush or slash may be more desirable than piling and burning when the soil is moist. The least severe water-repellent condition occurs during a 5-min burn over wet sand. Although this latter combination of soil water and burning time is least often found under natural conditions, it could be attained by desiccating standing brush and then burning when the soil was wet. If water repellency is an important consideration then, land managers may wish to select those conditions of soil water which minimize its occurrence.

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